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# Speed Control Law for Precision Terminal Area In-Trail Self Spacing

*Terence S. Abbott*  
*Langley Research Center, Hampton, Virginia*

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*Langley Research Center, Hampton, Virginia*

National Aeronautics and  
Space Administration

Langley Research Center  
Hampton, Virginia 23681-2199

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## Abstract

*This document describes a speed control law for precision in-trail airborne self-spacing. This control law was designed to provide an operationally viable means to obtain a desired runway threshold crossing time or minimum distance, one aircraft relative to another. The control law does not require any special Automatic Dependent Surveillance Broadcast (ADS-B) message, compensates for dissimilar final approach speeds between aircraft pairs, and provides guidance for a stable final approach. This algorithm has been extensively tested in Monte Carlo simulation and has been evaluated in piloted simulation, with preliminary results indicating acceptability from operational and workload standpoints.*

## Introduction

Concepts for in-trail self-spacing of aircraft operating in an airport terminal area have been under development by the National Aeronautics and Space Administration (NASA) since the 1970's (ref. 1). Interest in these concepts have recently been renewed due to a combination of emerging, enabling technology (Automatic Dependent Surveillance Broadcast data link, ADS-B) and the continued growth in air traffic with the ever increasing demand on airport (and runway) throughput. Terminal area, self-spacing has the potential to provide an increase in runway capacity through an increase in the accuracy of over-the-threshold runway crossing times, which can lead to a decrease of the variability of the runway threshold crossing times (ref. 2). Figure 1 depicts a typical runway arrival rate distribution. The average arrival rate for a particular runway is dictated primarily by the missed approach rate. (Aircraft with an in-trail separation closer than the separation criteria are required to perform a missed approach.) That is, the maximum average arrival rate for a runway is based on the maximum number of acceptable missed approaches; with the missed approach number driven by the minimum Air Traffic Control separation criteria and the in-trail separation variability around this average. By reducing the variability and maintaining the same missed approach rate, the average crossing time can be reduced, resulting in an increase in the number of landings a runway can accommodate over a fixed period of time (fig. 2).

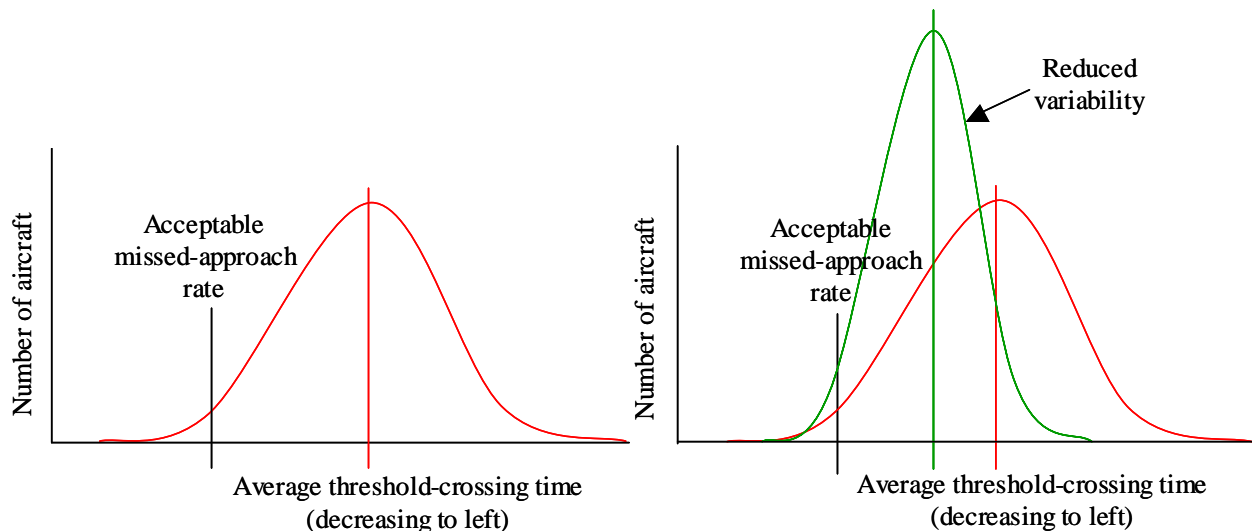


Figure 1. Typical distribution.

Figure 2. Typical and reduced-variability distributions.

One of the easiest in-trail spacing concepts to understand and implement is the fixed-distance concept. In this concept, each aircraft maintains a fixed-distance behind the aircraft it is following. The problem with this concept is that terminal area operations involve successive speed reductions by the landing aircraft. With a fixed-distance concept, when the in-trail spacing is obtained, the following aircraft then continually matches the current speed of the aircraft it is following. With multiple aircraft in-trail, the last aircraft will be speed-matching with the very first aircraft. This will result in following aircraft performing speed reductions at distances continually further from the airport (fig. 3). This may result in increased aircraft fuel consumption and higher generated noise. It should be noted, however, that traditional Air Traffic Control operations successfully use fixed-distance spacing by changing (reducing) the spacing interval as they reduce the in-trail speed.

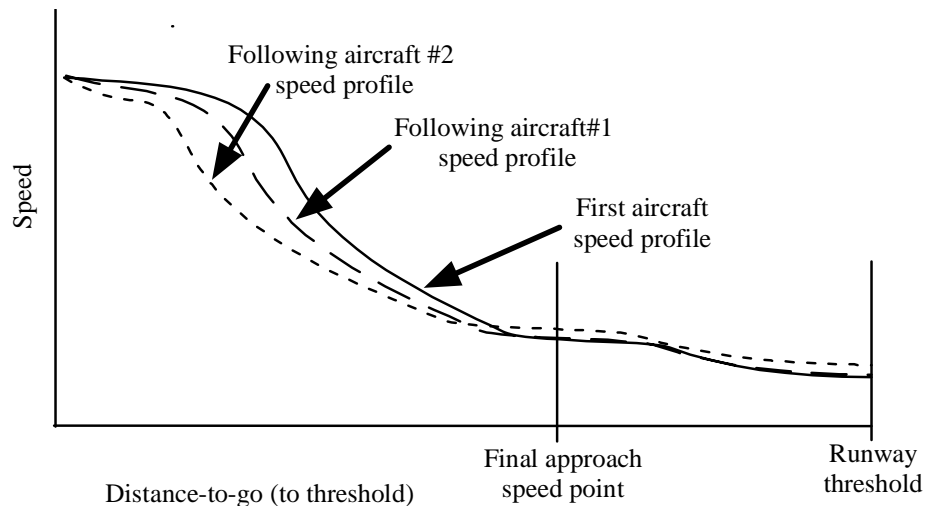


Figure 3. In-trail slow-down with constant-distance spacing.

One of the more promising concepts, from an operational acceptability and efficiency standpoint, is the time-history (also known as time-delay) concept. In this concept, each successive aircraft attempts to fly the speed profile of the aircraft it is following. For example, if the spacing goal were to maintain a 90 second spacing, then the following aircraft (ownship) will attempt to be at a speed and position where the leading aircraft (traffic) was 90 seconds earlier. Again, this generic concept was developed and evaluated in the mid-1980's by NASA (ref. 1). A renewed interest in approach spacing has been fostered by the realistic potential for the fielding of an airborne data link (ADS-B). Additional interest by the FAA's Safe Flight 21 Program has also encouraged other organizations to examine airborne approach spacing concepts (ref. 3). The concept described in this paper is that of a new, closed-loop control law that is a unique implementation and refinement of this time-delay concept.

## Nomenclature

ADS-B	Automatic Dependent Surveillance Broadcast
ATC	Air Traffic Control
FAA	Federal Aviation Administration
FMS	Flight Management System

goal-time	desired spacing interval, sec.
IAS	indicated airspeed
ownship	from a flight crew's perspective, aircraft that they are flying
traffic	from a flight crew's perspective, aircraft that they are following

## Algorithm Design

### Preliminary Concept for In-Trail Following

The fundamental aspects of this time-history concept are given in the following example. Assume that ownship is to follow a traffic aircraft at a 90-second time-spacing interval (the goal-time). Also assume that ownship is slightly behind where the traffic was 90 seconds ago. This example is shown in figure 4. From this situation, it is obvious that ownship needs to fly faster than the traffic to reduce this position error. The speed error value computed by this speed control law does produce a speed-error term designed to reduce this position error. This speed error term is then added to a "base speed" value to obtain a speed command value. In this concept, the "base speed" is the traffic aircraft's previous speed at ownship's current distance. This feature is shown in figure 5. The effect of using this technique (base speed) is that ownship will always close on the position error when the command speed is being satisfied.

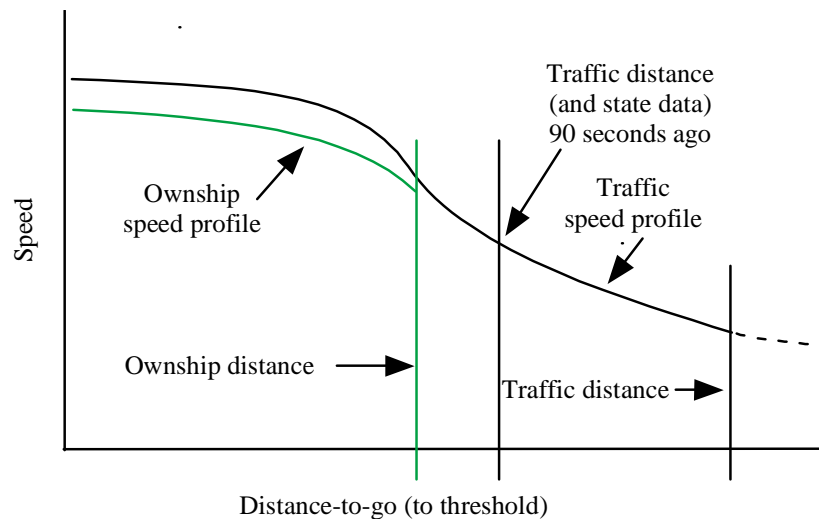


Figure 4. Example situation.

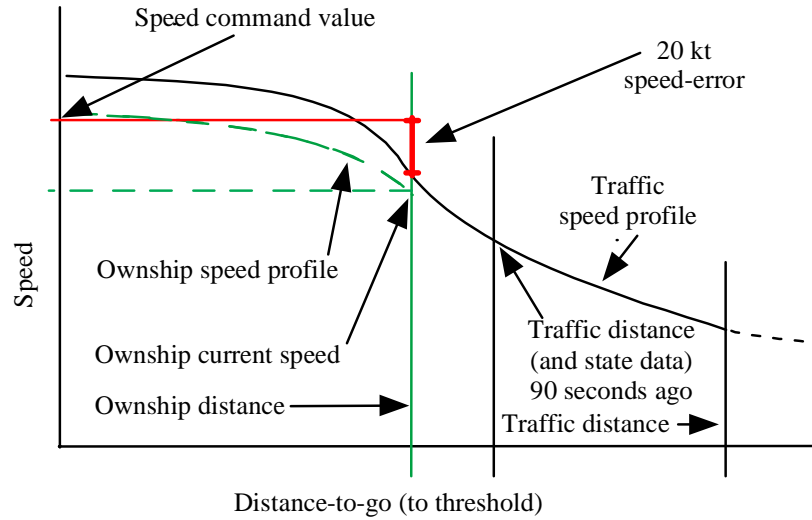


Figure 5. Command speed based on the traffic's goal-time speed

Given this conceptual overview, the resulting control law, known as the position, velocity, and acceleration spacing control law, is computed as shown in figure 6:

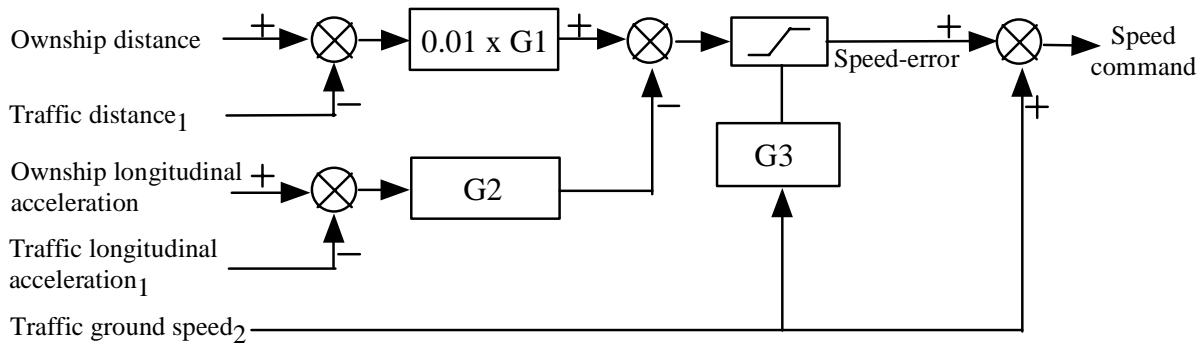


Figure 6. Initial control law implementation.

where distance units are in ft, speed units are in ft / sec, and acceleration units are in ft / sec<sup>2</sup>. The distance values are the along-track distance to the runway threshold. Also, note that variables subscripted with "1" are from the traffic's state data at the goal-time position and variables subscripted with "2" are from the traffic's state data at the ownship's current position. In this implementation, G1 is the range error gain and is 2.5 / sec; and G2 is the differential-acceleration gain and is 2.5 sec. G3 is the speed-error limit gain and is 0.1 for this implementation. Thus, the speed-error value is limited to  $\pm 10$ -percent of the traffic's previous ground speed at the ownship's current position. Note that the along-track distance values are computed using a straight-line calculation to the runway threshold. Thus, this specific implementation is only usable when the aircraft are on final approach (but would be useable if the along-track distance were provided by any other means, e.g., FMS).

From an operational standpoint, a ground speed command is not appropriate for pilot procedures. The ground speed command must be converted to an airspeed command to be usable by a pilot. This can be done through a standard speed conversion to include a wind speed component.



In addition, from an operational standpoint, speed-limiting values (maximum and minimum) should be imposed on the airspeed command. For example, the airspeed command should never command a speed lower than ownship's minimum landing speed, so one of the limiting, minimum speed values should be the minimum landing speed.

## Nominal Speed Profile Revision for Enhanced System Performance

While the previous section noted the benefit of using the traffic's ground speed as the speed basis (to which the speed error term is added), an FAA-sponsored flight test and further Monte Carlo simulations have shown that an alternative approach may be more beneficial from a system-performance standpoint. These simulations showed that using a nominal speed profile as the speed basis would provide better runway threshold crossing-time performance for large (long) approach streams. System performance improvements were noted with reductions in both average crossing-time interval errors and the number of required missed approaches (when aircraft are too close). With this concept, a single, nominal speed versus distance-to-go profile is used by all of the aircraft in the approach stream. (Note that for an "unequipped aircraft," one without this control law but with ADS-B, a simple procedure will allow these aircraft to participate as the "leading aircraft.") As noted in the previous discussion, the speed error term is added to this nominal speed value. The use of small speed perturbations around a nominal speed was found to increase overall system performance (many aircraft in the stream) relative to just closely matching the traffic's speed. When using this nominal speed profile concept, it was also found that removing the acceleration input in the control law also enhanced system-wide performance. An example of a nominal speed profile is given in figure 7. It should again be noted that this speed versus distance profile could be included in a standard arrival procedure for an airport. An example of a representative Monte Carlo output using this concept is given in figure 8. The modified control law is shown in figure 9.

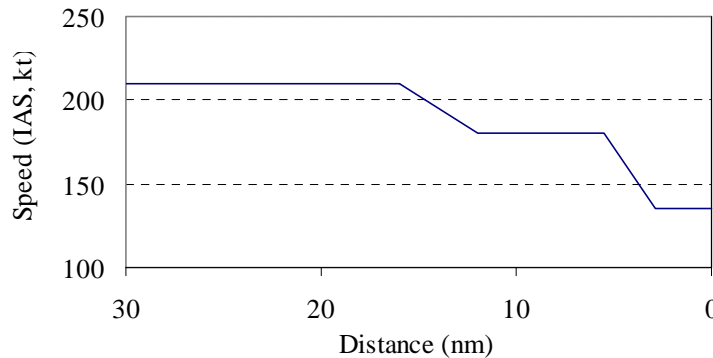


Figure 7. Typical nominal speed profile.

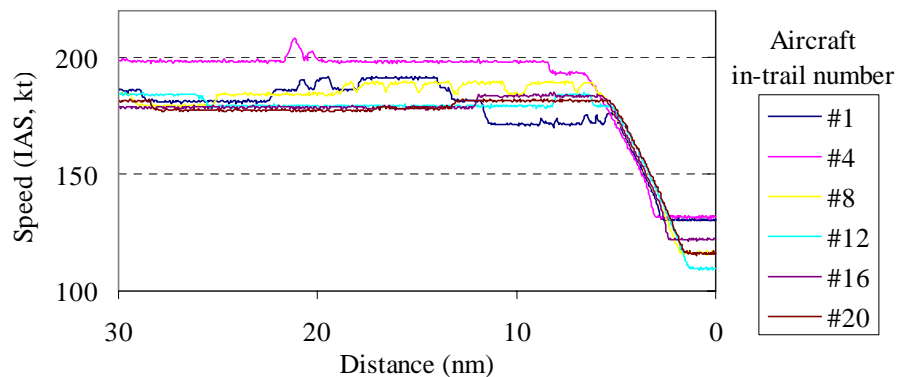


Figure 8. Representative speed profiles from Monte Carlo simulation.

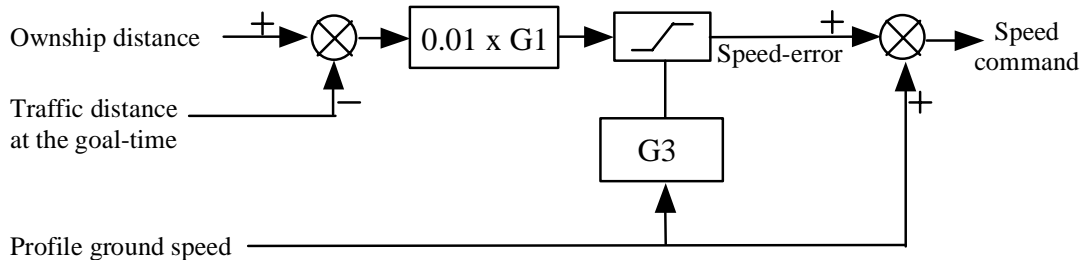


Figure 9. Modified control law.

As in the original control law, the distance units are in ft and speed units are in ft / sec. The distance values are the along-track distance to the runway threshold. The profile ground speed is the planned speed profile at ownship's current position, converted to ground speed. G1 is the range error gain and is 2.5 / sec; and G3 is the speed-error limit gain and is 0.1 for this implementation.

### Computation of Nominal In-Trail Time

Since this algorithm is designed to provide a stable, constant speed segment prior to the threshold (i.e., a stabilized approach), the speed command transitions from actively tracking the in-trail separation to the final approach speed. This transition is initiated at a specified distance (the deceleration point) from the threshold (e.g., 5 nmi) and occurs along a scheduled deceleration profile. Given the requirement for a stabilized approach, if ownship and the traffic have different final approach speeds then the actual relative threshold crossing time will be different from the desired threshold crossing time (if the algorithm spaces to the desired threshold crossing time interval). To resolve this problem and compensate for dissimilar final approach speeds, the following calculations are made:

1. For both the traffic and ownship, their respective speed profiles, including the planned final approach speeds, are converted to ground speed using a blend of current and estimated wind speeds.
2. Using these ground speed profiles, the time from the deceleration point to the threshold is computed for both aircraft
3. Using the computed times from above, a threshold crossing time adjustment (GoalTimeAdjustment) is calculated and is the traffic-time-to-threshold - ownship-time-to-threshold.
4. The adjusted desired time is then calculated and is the original desired threshold crossing time interval + GoalTimeAdjustment (i.e., original desired threshold crossing time interval + traffic-time-to-threshold - ownship-time-to-threshold).

### Computation of In-Trail Time for Minimum Spacing

Based on further Monte Carlo analysis, an option was added to maximize runway throughput under special conditions. It was noted that the maximum potential throughput occurs when each aircraft pair spaces to the minimum allowed in-trail distance (i.e., paired-dependent, wake-vortex separation distance). This option allows the algorithm to internally calculate the point in time at which minimum in-trail separation will occur (from an input of the minimum allowed separation distance and the final approach

speeds of the two aircraft) and the resulting required spacing time, "backing-out" this time from the nominal profile.

If the intent is to perform a minimum spacing approach, where the desire is a minimum distance interval, then a technique similar to the computation of nominal in-trail time is used. To compute a spacing time interval that will result in a minimum separation interval, the following calculations are made:

1. For ownship, convert the speed profile, including the planned final approach speed, to ground speeds using a blend of current and estimated wind speeds.
2. Using the ground speed profile, compute the time (MinTime) to fly a distance equal to DistanceMinima + DistanceMinimaBuffer;

where DistanceMinima is the minimum in-trail separation distance (an input variable) and DistanceMinimaBuffer (currently set to 0.10 nmi) is an additional safety buffer.

The adjusted desired time is then calculated and is MinTime + GoalTimeAdjustment (previously defined).

### **Prevention for Loss of Minimum In-Trail Distance Separation**

An additional variable was added to the original algorithm, a minimum in-trail separation distance (typically the pair-dependent vortex separation distance). This variable is used in a calculation to determine if the minimum in-trail distance is predicted to be lost at some time during the approach. Several calculations are used to determine if this condition is true (potential loss of minimum in-trail distance) and if true, the resulting speed command. The calculations are as follows:

$$\text{DistanceToMinimum} = \text{OwnshipDTG} - \text{ComputedMinDist};$$

where DistanceToMinimum is the range-to-minimum-distance, OwnshipDTG is the ownship's distance (along path) to the threshold, and ComputedMinDist is the computed-minimum-distance.

$$\text{ComputedMinDist} = \text{DistanceMinima} + \text{DistanceMinimaBuffer} + \text{RangeBias} + \text{TrafficDTG};$$

where DistanceMinima is the minimum in-trail separation distance (the input variable described above), DistanceMinimaBuffer (currently set to 0.10 nmi) is an additional safety buffer, RangeBias is a range-bias to compensate for dissimilar final approach speeds, and TrafficDTG is the traffic's distance (along path) to the threshold.

RangeBias is set to 0.0 if the ownship's final approach speed (converted to ground speed), OwnshipFinalGndSpd, is less than the traffic's final approach speed (converted to ground speed), TrafficFinalGndSpd, otherwise:

$$\text{RangeBias} = (\text{OwnshipFinalGndSpd} - \text{TrafficFinalGndSpd}) * \text{GoalTimeAdjustment};$$

where GoalTimeAdjustment is defined in the section entitled Computation of Nominal In-Trail Time.

Two conditions must be met for this special case to become active and override the standard speed command. These two conditions are a distance test that evaluates the closure to minimum distance and a speed test that evaluates the rate of closure.

The distance test, DistTest, is computed as:

$$\text{DistTest} = \text{VTest1} * \text{TimeTest},$$

where:

If (ownship's ground speed – 10 kt) is greater than Vcmd, VTest1 = ownship's ground speed – 10 kt;

else if (ownship's ground speed + 30 kt) is less than Vcmd, VTest1 = ownship's ground speed + 10 kt;

else VTest1 = Vcmd; where Vcmd is the original commanded ground speed for the algorithm.

$$\text{TimeTest} = \text{TrafficDTG} / \text{TrafficFinalGndSpd};$$

The speed test, VTest2, is calculated from the minimum distance point to ownship's position along a nominal deceleration schedule, DS:

$$\text{VTest2} = \text{TrafficGndSpd} + [2 * (\text{OwnshipDTG} - \text{ComputedMinDist}) * \text{DS}]^{1/2};$$

where TrafficGndSpd is the traffic's ground speed.

Finally, the test for these two cases for a potential loss of in-trail separation is:

If (VTest1 is greater than VTest2) and (DistTest > (OwnshipDTG - DistanceMinima - DistanceMinimaBuffer - RangeBias)) then a potential separation loss may occur with the current Vcmd value.

If this condition is true and Vcmd is greater than VTest2, set Vcmd = VTest2. Additionally, set a lower limit on this new Vcmd value to TrafficGndSpd – 5 kt.

This technique has been evaluated in Monte Carlo and piloted simulation and appears to provide a reasonable means for handling the unusual event of the traffic aircraft being significantly off the speed profile.

### **Off-Final In-Trail Following**

An additional enhancement was made to this concept to support off-final, in-trail spacing. In this situation, ownship is simply in-trail behind the traffic, with no knowledge on the along-path distance to the runway threshold. The inputs to the modified control law were changed for this situation such that:

The traffic's current distance is assigned some arbitrary large value and both the traffic-distance-at-the-goal-time and ownship-distance are measure relative to this arbitrary value.

The profile ground speed is changed to the traffic's ground speed at the goal-time.

This addition enhances the operational viability of this control law by providing a means for in-trail following in the airport terminal area. The algorithm transitions to the control law of figure 9 once both aircraft are on final approach.

## Summary

The algorithm described in this document is a preliminary concept for a precision in-trail self-spacing tool. This tool is implemented as a speed control law with the following considerations in its design:

1. Provides speed commands to obtain a desired runway threshold crossing time or minimum distance, one aircraft relative to another.
2. Does not require any special Automatic Dependent Surveillance Broadcast (ADS-B) message.
3. Compensates for dissimilar final approach speeds between aircraft pairs.
4. Includes wake vortex minima requirements.
5. Provides guidance for a stable final approach speed.

This algorithm has been evaluated in piloted simulation, with preliminary results indicating acceptability from operational and workload standpoints.

## References:

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2. Swedish, W. J.: *Evaluation of the Potential for Reduced Longitudinal Spacing on Final Approach*, FAA-EM-79-7, August 1979.
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